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RECENT ELEVATION CHANGE IN SOUTHERN CALIFORNIA

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ABSTRACT. Velocities of elevation change for two time periods have been determined from Southern California leveling data. Two periods were selected for study: 1906 through 1962 and 1959 through 1976. The study area extends from San Pedro north to latitude 35.°5, and between longitudes 117° and 119.°5. The shape of the fitted velocity surface for the latter epoch agrees with the original uplift established by Castle et al. (1976) with the exception that no eastern termination is evidenced within the study area. The velocity surface for the earlier time period shows negligible subsidence of 1 mm/yr at Palmdale, increasing to 9 mm/yr at Bakersfield. The 11 mm/yr maximum uplift velocity determined for the period 1959 through 1976 is approximately twice the corresponding standard deviation. Weighted velocities, extracted from tidal records at six stations on the coast, were used to provide input for absolute height change.

INTRODUCTION

Because of the concern associated with crustal uplift in Southern California, an attempt has been made by the National Geodetic Survey (NGS) to obtain the best estimates possible of its character, magnitude, and areal extent. Tide gage records and repeated leveling surveys have been combined in a least-squares adjustment, using a computerized program, SURFACE, to accomplish this task. SURFACE solves for heights of selected points at a selected reference time and for coefficients of a polynomial which expresses height change as a function of latitude and longitude.

Castle et al. (1976) suggest that the uplift began around 1960. For this reason the analysis described in this report is given in two parts. The first part concerns tide gage and leveling data existing prior to late 1962; the second part treats data originating after early 1959.

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The NGS investigation of Southern California elevation change had the following specific objectives:

1. Test the early conclusion that insignificant aseismic vertical deformation had taken place prior to 1960.

2. Test the early conclusion that significant aseismic vertical deformation began after 1960.

3. Determine a velocity (of elevation change) surface for each study period to describe the pattern of characteristic motion.

4. Isolate locations which exhibit nonlinear vertical movements during the recent study period.

The geographical limits of the study area are shown in figure 1, along with the locations of tide gages and major faults. Figure 2 shows the locations of levelings used in the investigation.

LEVELING DATA

Most levelings in Southern California naturally fall into epochs which have lasted several years. During this time, surveying activity would be intense. Then, typically, a period would follow in which leveling activity would be minimal. The oldest levelings used in this investigation date back to 1906. A great many original levelings, and some relevelings, were accomplished between 1926 and 1929. A significant releveling effort was made in 1946, but it was not extended northward beyond San Fernando. Although levelings were accomplished in a time-scattered manner for the next 14 years, another major releveling of the study area was not accomplished until 1959-62.

Extensive network relevelings were performed in the epochs 1968-69 and 1973-74, with individual net segments being acquired at various intermediate and later times.

Two adjustments were performed to evaluate the preliminary conclusions mentioned in the introduction. Levelings made prior to 1962 have been used in adjustment I to estimate the magnitude, pattern, and constancy of movement for the early period. The 1959-62 epoch levelings were also used, with the 1968-69 and 1973-74 epoch measurements in adjustment II to determine corresponding information for the more recent period.

All of the leveling data used in adjustments I and II are first-order measurements, i.e., they are of the highest precision.

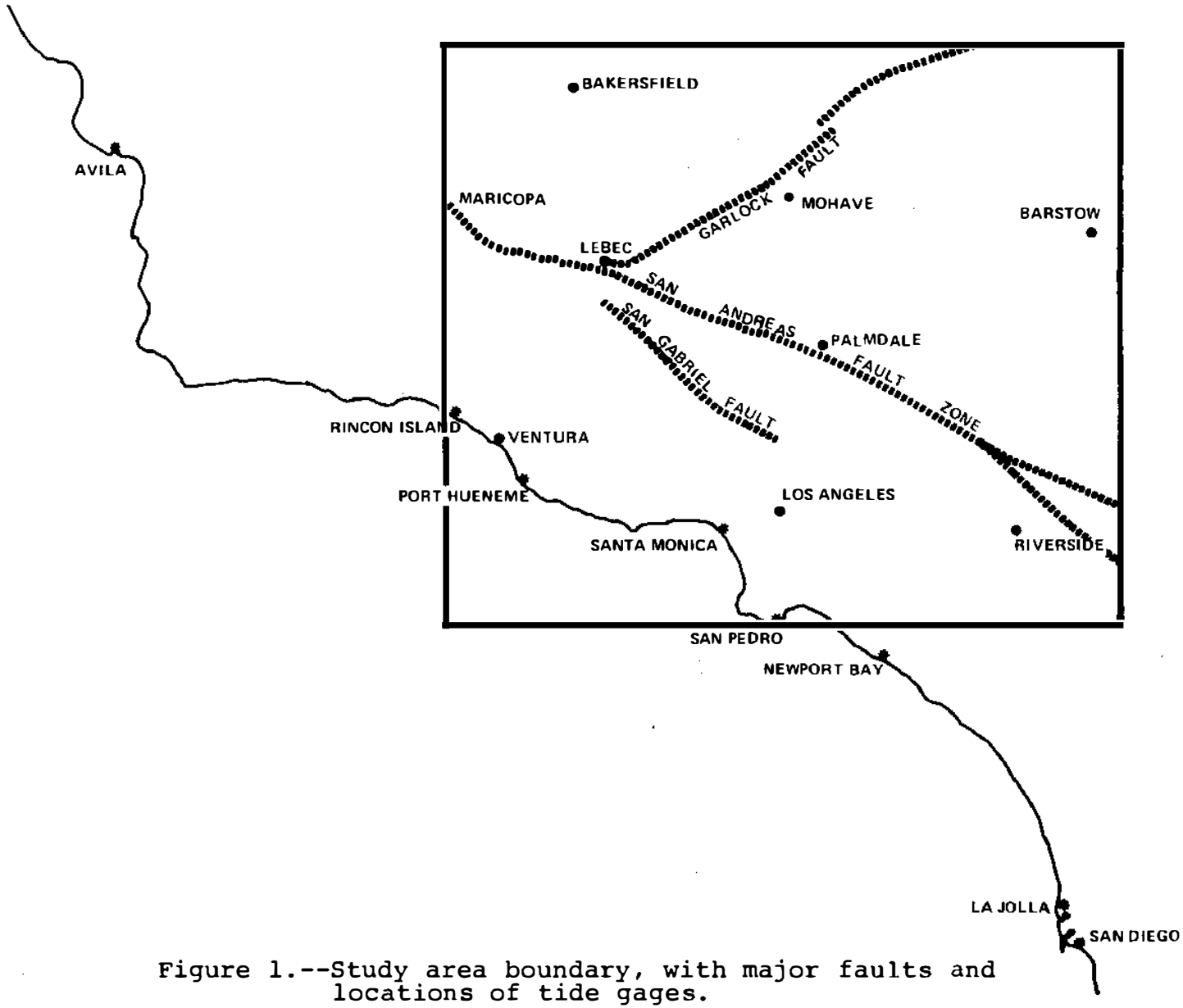

Figure 1.--Study area boundary, with major faults and locations of tide gages.

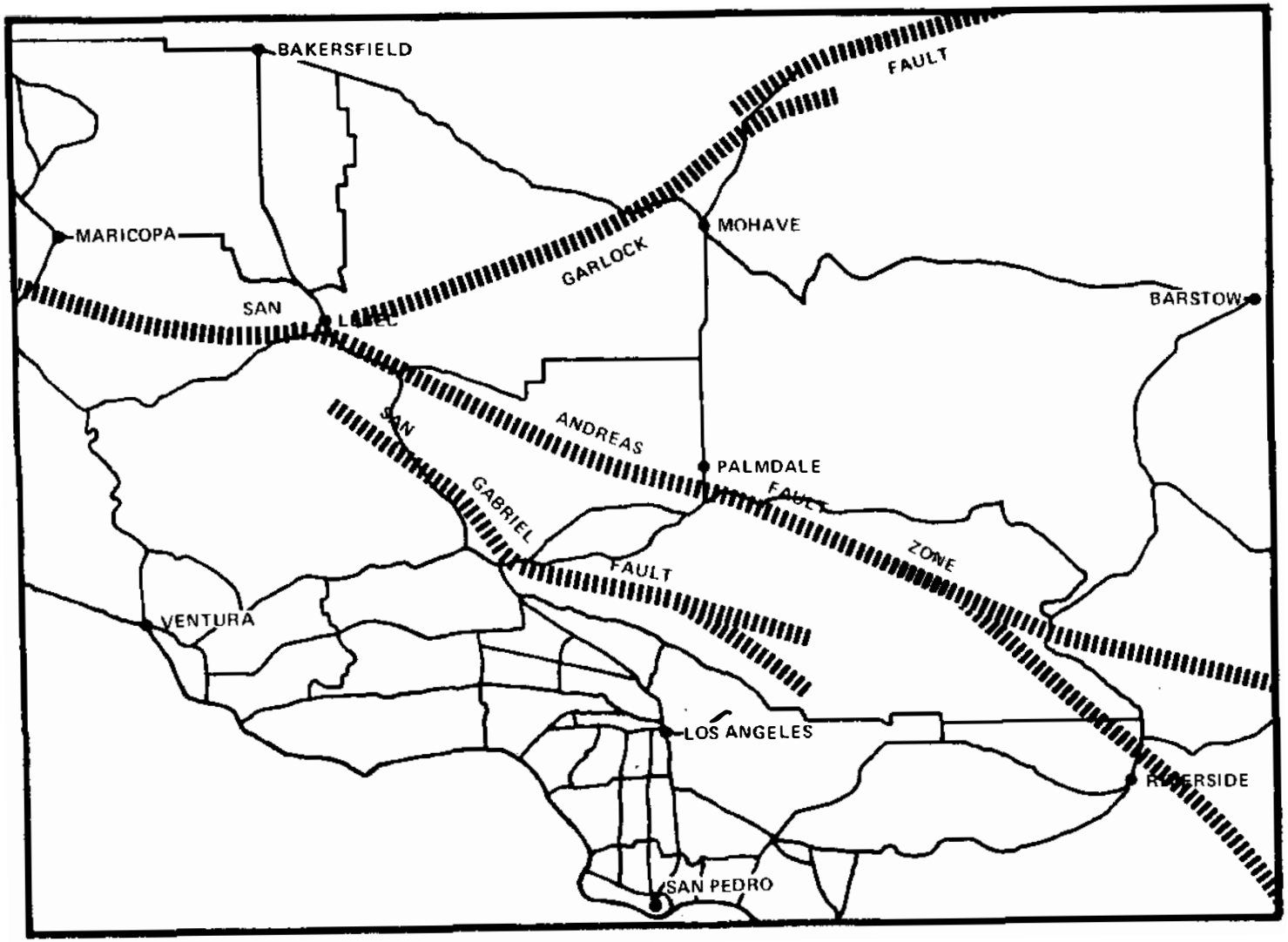

Figure 2.--Locations of level lines used to estimate uplift.

TIDAL DATA

The locations of the tide gages which were used in the analyses are shown in figure 1. Specific details concerning the stations are summarized in table 1.

Estimates of absolute velocities have been extracted from the tidal records by assuming that the secular change in sea level relative to the tidal bench mark has two basic components: (1) the eustatic or worldwide rise in sea level, and (2) the apparent change in sea level due to local and regional vertical movement of the land. The eustatic rise was taken as +1.0 mm/yr. The height change velocities at the locations of the tide gages were derived by fitting straight lines through plots of annual mean sea levels (see fig. 3). The slopes of these lines are considered to represent the velocities at which the sea was rising with respect to the land at each tide station. By reducing the slope to account for the eustatic rise of sea level, and changing the sign, a value was obtained for the velocity at which the land moves vertically with respect to a stable reference. The standard deviations of the slopes of the fitted lines were taken as the standard deviations of the corresponding velocities of elevation change at the tidal bench marks.

The annual mean sea level (MSL) values that were used in the study were not corrected for meteorological or other conditions. Wherever possible, two velocities (corresponding to the pre-62 and post-59 periods) were determined for input to the surface fitting process. For adjustment II, the annual MSL values from 1957 to 1975 were used. This eliminated bias that might have been introduced when using data which did not extend over an 18.6 year astronomical cycle.

The direct estimation of velocity at each tide gage provides the only absolute information in adjustments I and II. Analysis of leveling data without these direct estimates can provide the shape of the deformed surface, but contour labels would only be meaningful in the relative sense. Weights given to the tide gage velocities were inversely proportional to the square of their standard deviations.

ADJUSTMENT METHOD

For any bench mark, A, in a study area, the following expression gives its height at time t_i:

$$h_{a,i} = h_{a,o} + V(x_a, y_a)\ (t_i - t_o) \qquad (1)$$

where, for example,

$$V(x_a, y_a) = c_o + c_1 X_a + c_2 Y_a + c_3 X_a Y_a + c_4 X_a^2 + \ldots. \qquad (2)$$

Table 1.--Tide gage stations in Southern California
(Velocities of elevation change are given in mm/yr.)

	Adjustment I			Adjustment II		
Gage Name	Velocity	Std. Deviation	Series	Velocity	Std. Deviation	Series
San Diego	-1.33	0.41	1926-62	+2.80	1.19	1957-75
La Jolla	-0.65	0.40	1925-62	+1.63	1.43	1957-75
Newport Bay				+1.38	1.22	1956-74
San Pedro	0.00	0.39	1924-62	+3.44	1.08	1957-75
Santa Monica	-2.16	0.65	1933-62			
Port Hueneme	-4.04	1.05	1941-62			
Rincon Is.				-5.62	2.67	1962-74
Avila	-1.87	1.02	1946-70	-1.87	1.02	1946-70

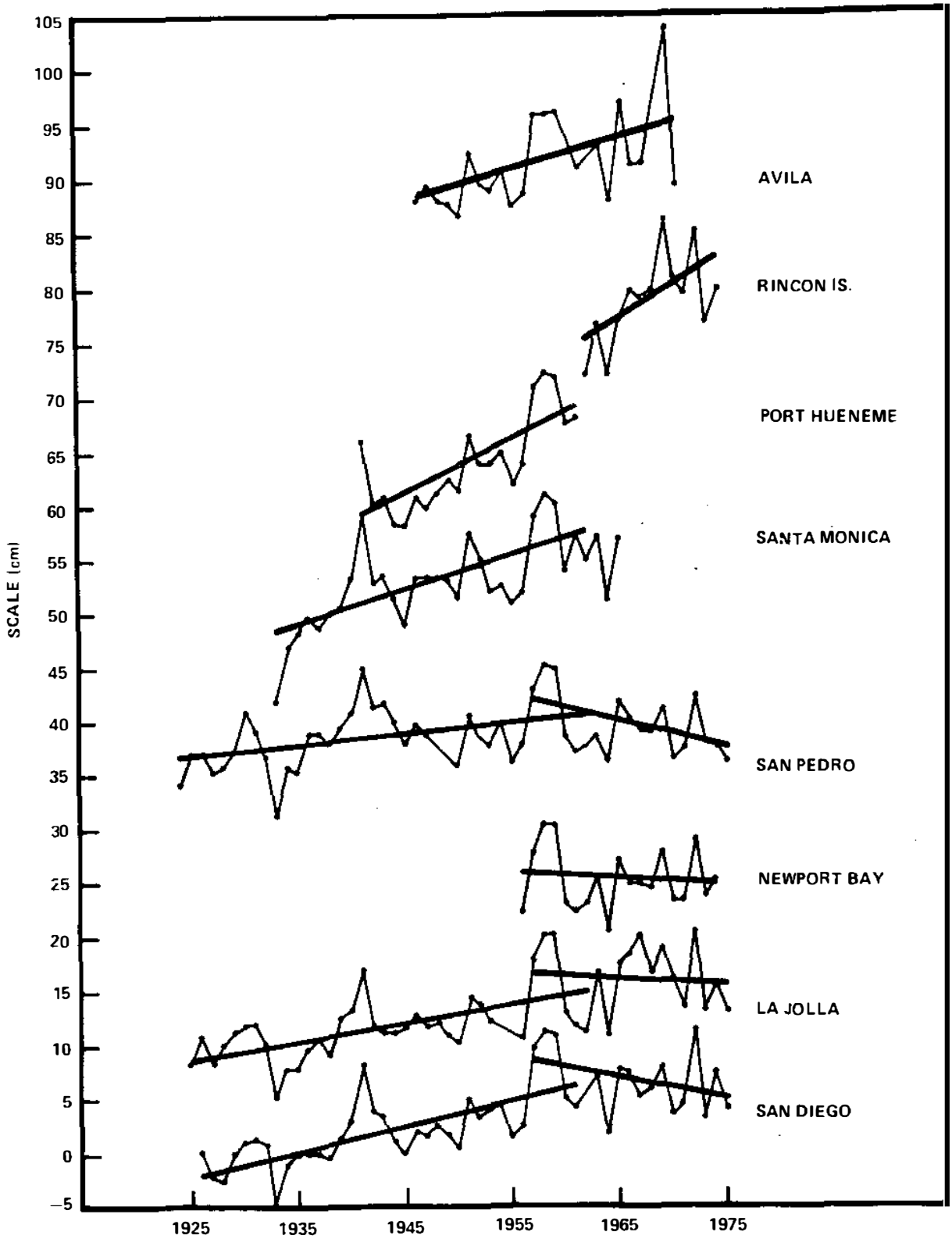

Figure 3.--Variation of mean sea level.

In equation 1, $h_{a,o}$ is the height of point A at the selected reference time, t_o; $V(x_a, y_a)$ is the velocity at location x_a, y_a. The unknowns in the adjustment are the height at each point corresponding to time t_o, and the coefficients c_k, k = 1, 2, 3, . . . m which define the velocity surface. If u is the number of unknown junction heights, then the total number of unknowns is u + m. The number m of coefficients is arbitrary and is limited only by the number of redundant observations. In adjustments I and II, involving the Palmdale area data, 24 coefficients were used. Note that the constant term in equation (2) drops out when the observation equation is formed:

$$R_{b-a,i} = h_{b,i} - h_{a,i} - \Delta h_{b-a,i} \qquad (3)$$

In (3) above, $R_{b-a,i}$ is the correction (residual) for the height difference $\Delta h_{b-a,i}$ observed at time t_i, between points A and B.

The development of this computational approach was motivated by the need for a flexible adjustment program to deal with vertical motion of bench marks in a level network (Holdahl 1975), and the need to obtain automated graphic display of vertical deformation and velocity error sources.

The merit in fitting a velocity surface to time-scattered and repeated leveling may not be obvious if elevation change is likely not to be occurring at constant rates. Actually, a variety of benefits results from the "surface fitting" type of leveling adjustment, when the leveling data are adequately redundant:

- The adjustment determines a surface, the shape of which reflects the accumulated deformation over the time range of the leveling observations.
- The average velocities of elevation change are determined for each locality in the study area.
- The linearity or constancy of the movement is evaluated statistically.
- Locations of abnormally nonlinear movements are isolated by the model.

The first benefit, determination of the shape of the deformed surface, is useful information regardless of whether the movement occurred episodically or uniformly. The estimated velocities are meaningful only if the model fits adequately. Adequate fit is evidenced by a small sum of weighted squared residuals. Adequate model fit means that movement is reasonably close to being constant with time over most of the study area.

In the adjustment each observation takes a correction. Observations taking large corrections may form a geologically meaningful pattern when plotted over the study area. A large residual is one which is several times the size of its standard deviation. The standard deviation of a residual can be computed rigorously, or can be approximated by, for example, the a priori standard deviation of the observation.

SUMMARY OF RESULTS

Figures 4 and 5 are contour and 3-dimensional representations of the velocity surface resulting from adjustment I. Figures 6 and 7 are the corresponding contour and 3-dimensional illustrations of the velocity error surface. It is important to view figures 4 through 7 together, so that conclusions can be made about the significance and reliability of the velocities. For example, it should be obvious from looking at figures 6 and 7 that lack of data in the Pacific Ocean, west of San Pedro, and in the desert north of Barstow, make velocities computed there very unreliable.

Figures 4 through 7, corresponding to the 1906-62 data analyzed in adjustment I, show that little vertical movement had accumulated during that period. Palmdale and Lebec exhibited negligible movement, while Maricopa and Bakersfield showed subsidence, which was most likely attributable to water withdrawal for agriculture. This general pattern of movement tends to verify the conclusions of Castle et al.(1976) that the study area did not exhibit broad aseismic motion prior to 1960.

Figures 8 through 11 were generated from adjustment II, using the data from 1959 through 1976. Comparison of figures 4 and 8 shows how striking the uplift has been during the later period. The new uplift velocities at Maricopa and Mohave are more significant when it is understood that these locations were previously moving downward. The only point which has preserved its pre-1962 velocity was Ventura. The velocity standard deviations in the fastest moving areas are about half as large as the velocities. This means the uplift should be regarded as a real phenomenon.

From the "goodness of fit" standpoint, neither adjustment I nor adjustment II was particularly successful. The standard deviation of an observation of unit weight from each adjustment was 12.6 mm and 8.2 mm, respectively. An observation of unit weight in these adjustments refers to a double-run measurement, one kilometer in length, performed according to first-order specifications. It might have been possible to achieve a better model fit if the number of coefficients used to describe the velocity surface had been increased. However, poor fit was more likely caused by the use of some junction bench marks that

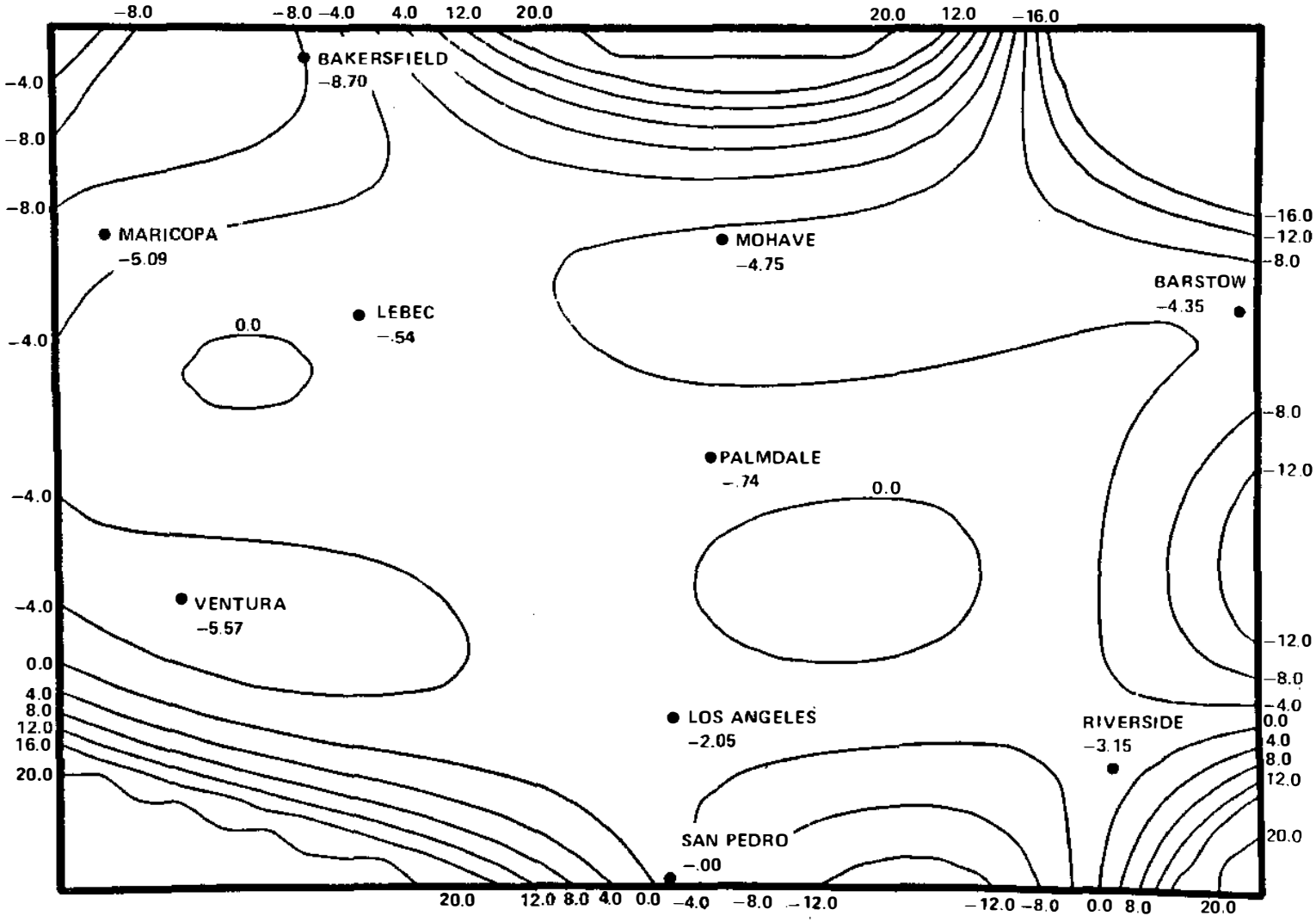

Figure 4.--Velocity contour map of Palmdale vicinity, 1906 - 1962 (units in mm/yr).

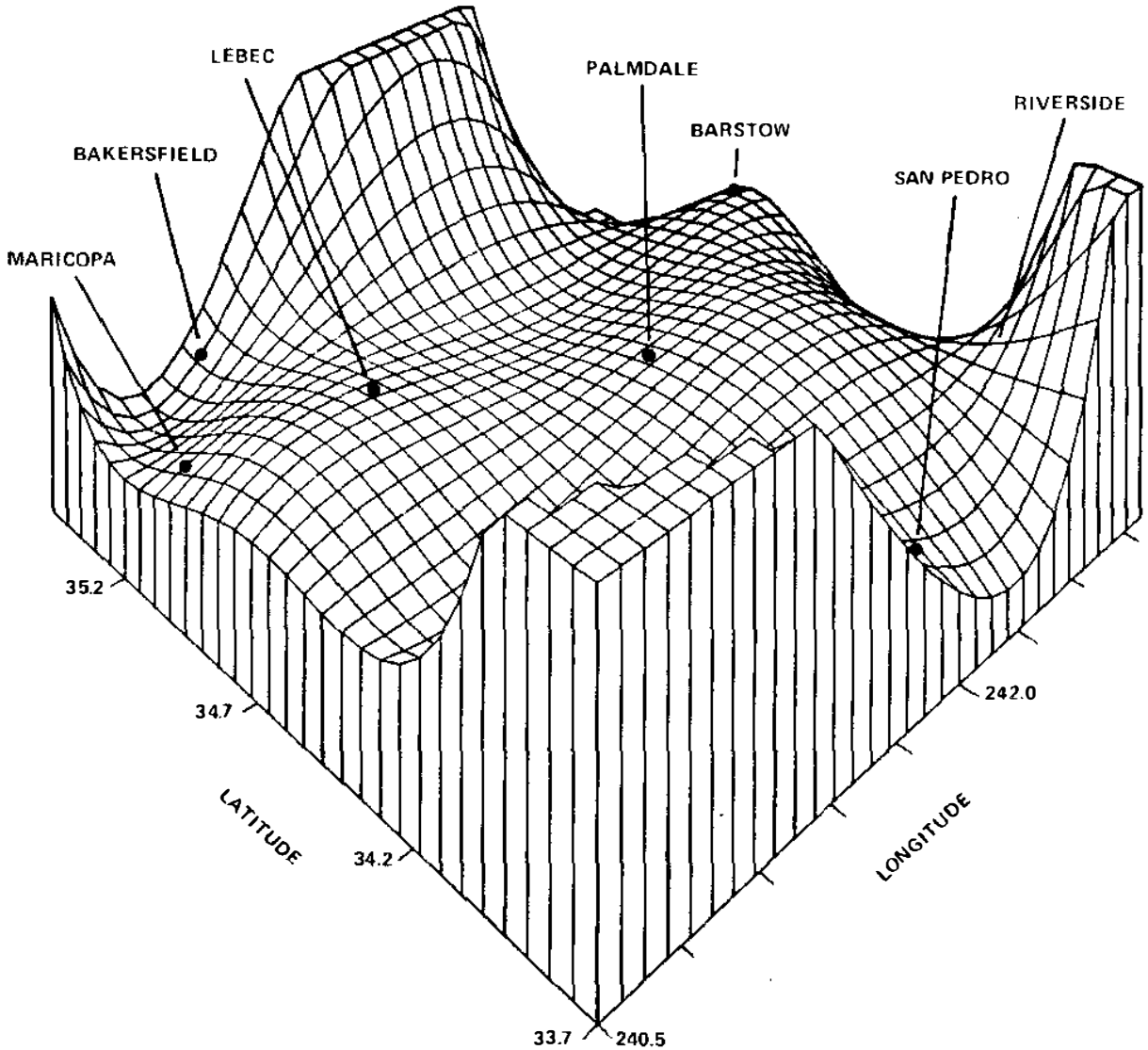

Figure 5.--Velocity surface in Palmdale vicinity, 1906 to 1962.

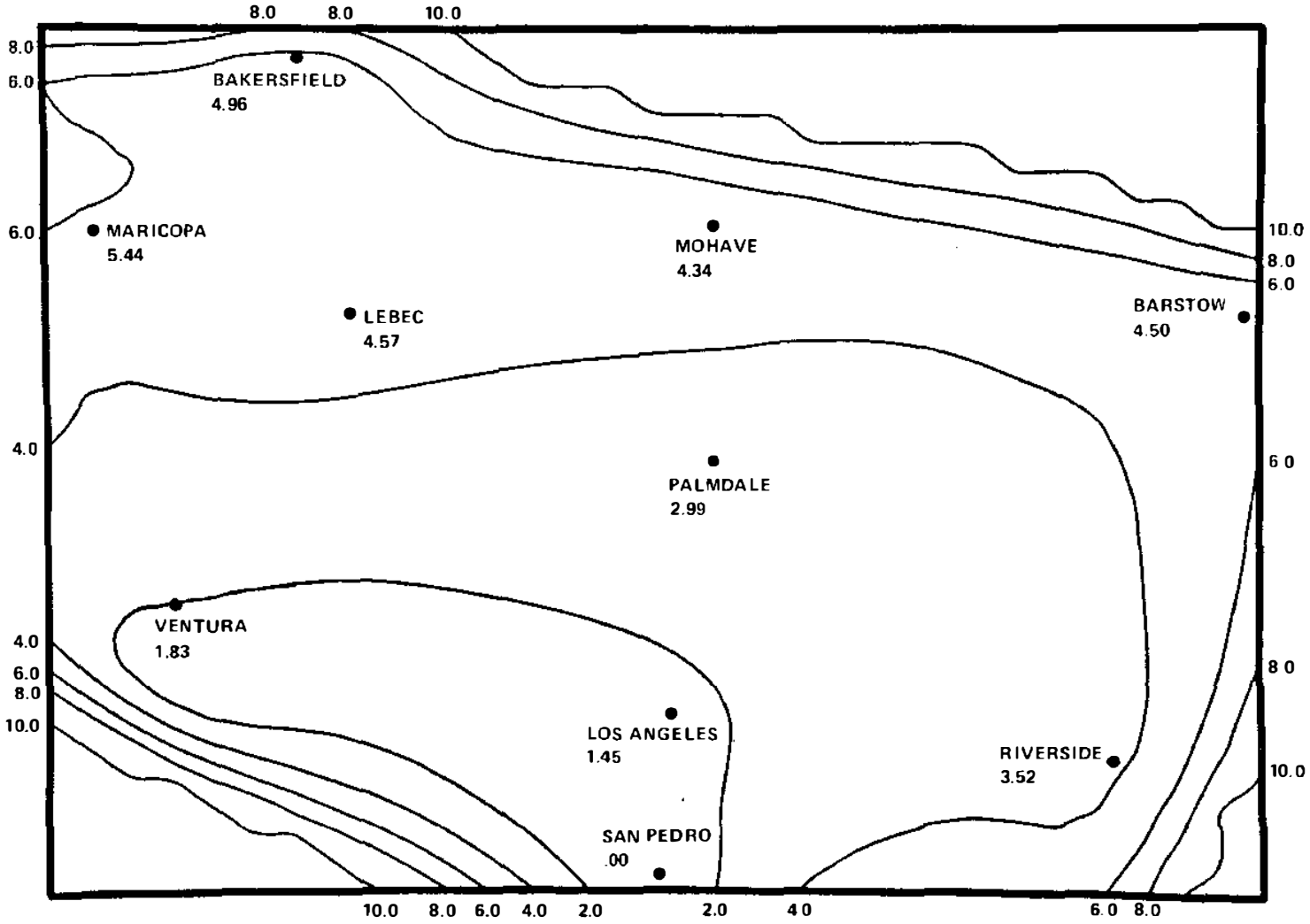

Figure 6.--Surface of velocity standard deviations in Palmdale vicinity, 1906 to 1962 (units in mm/yr).

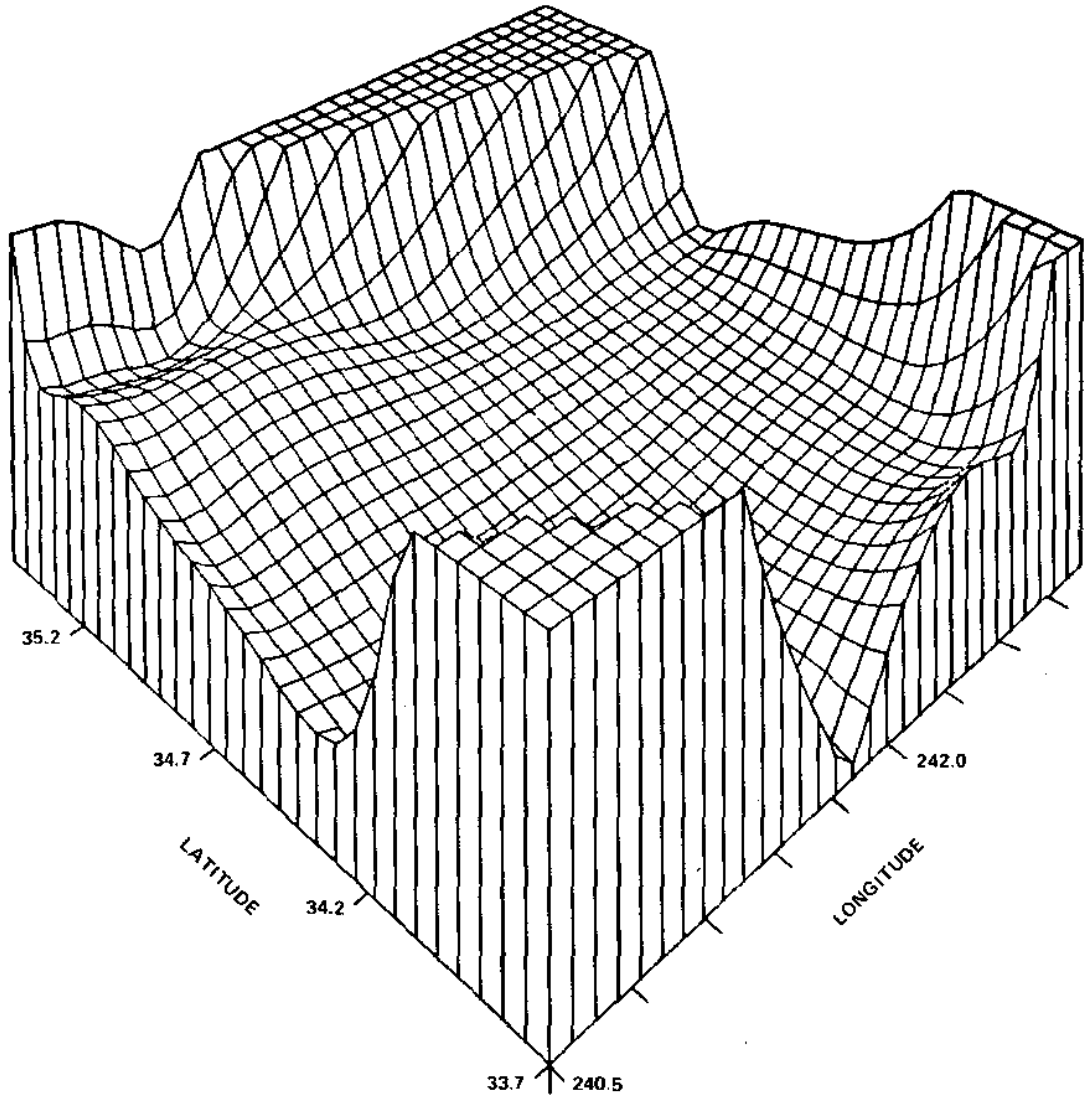

Figure 7.--Velocity error surface in Palmdale vicinity, 1906 to 1962.

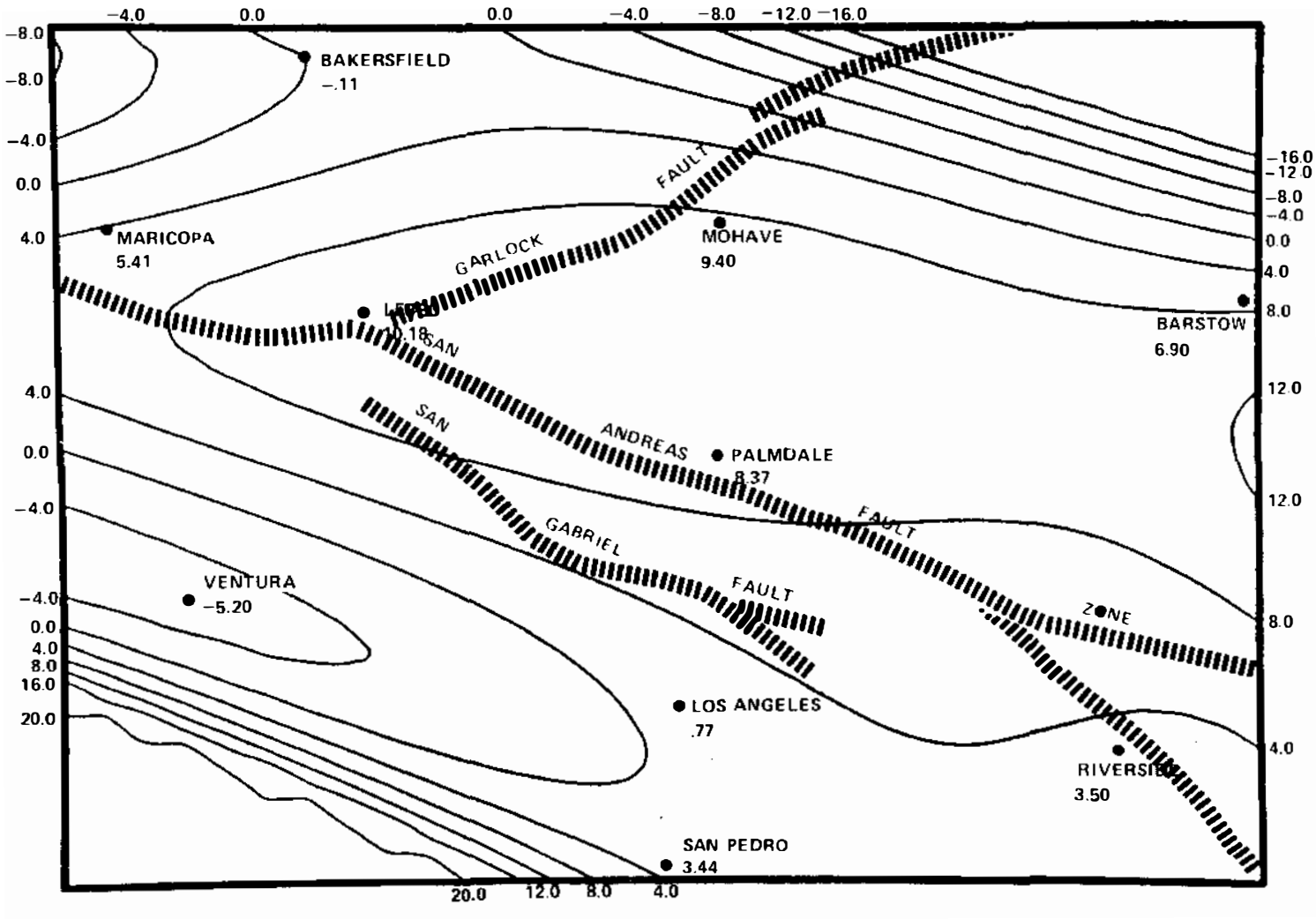

Figure 8.--Velocity contour map for Palmdale vicinity, 1959 to 1976 (units in mm/yr).

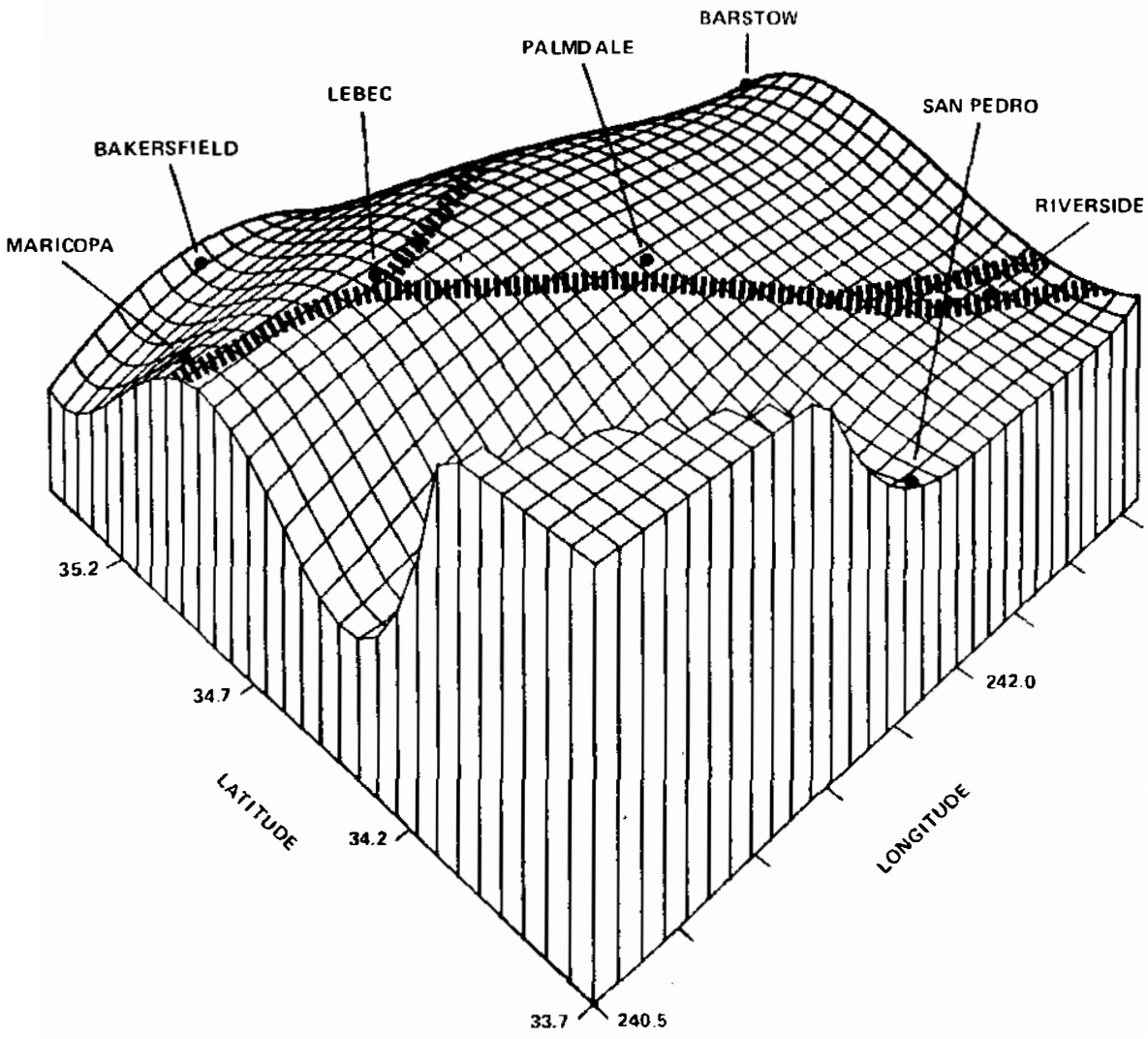

Figure 9.--Velocity surface for Palmdale vicinity, 1959 to 1976.

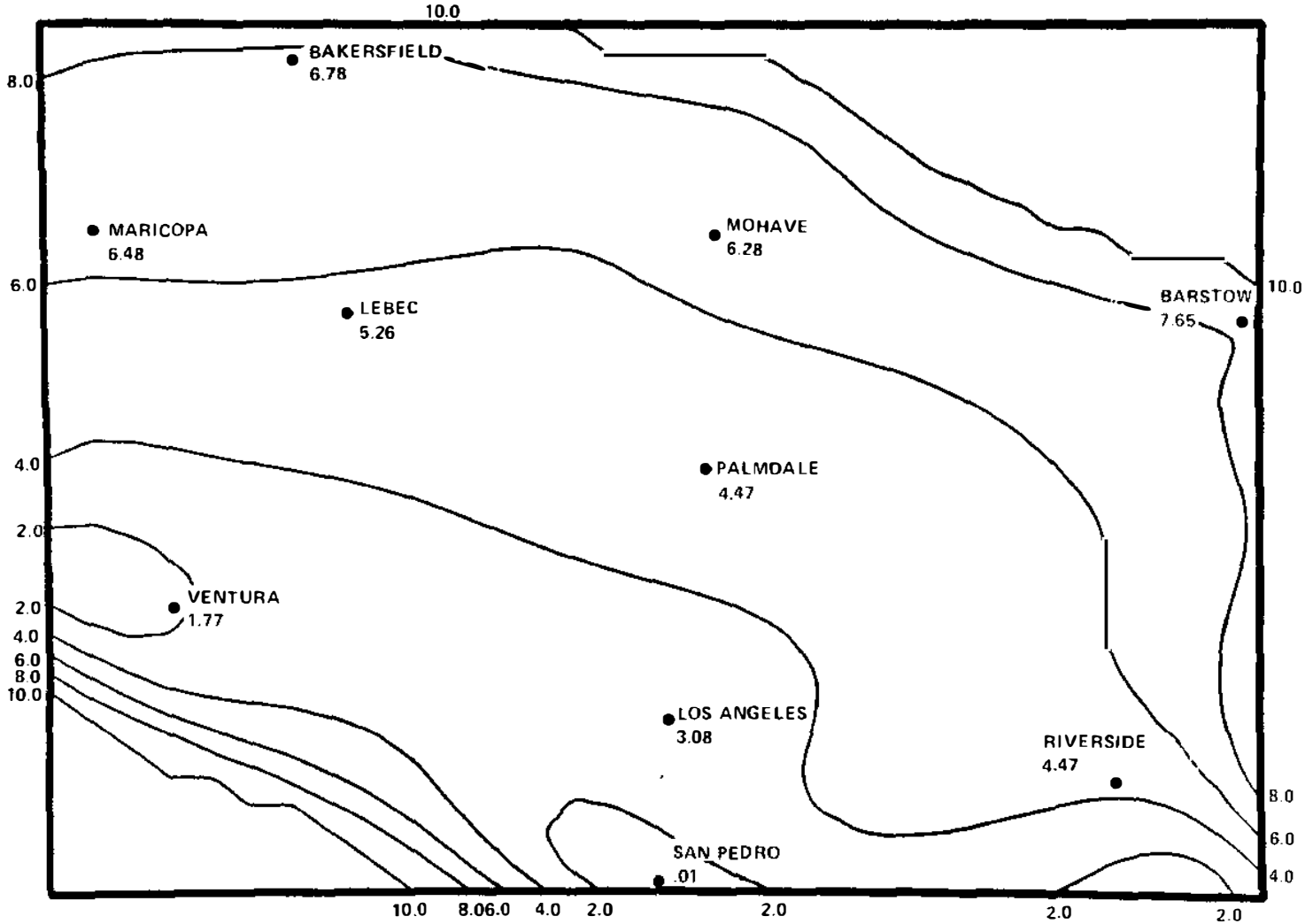

Figure 10.--Surface of velocity standard deviations for Palmdale vicinity, 1959 to 1976 (units in mm/yr).

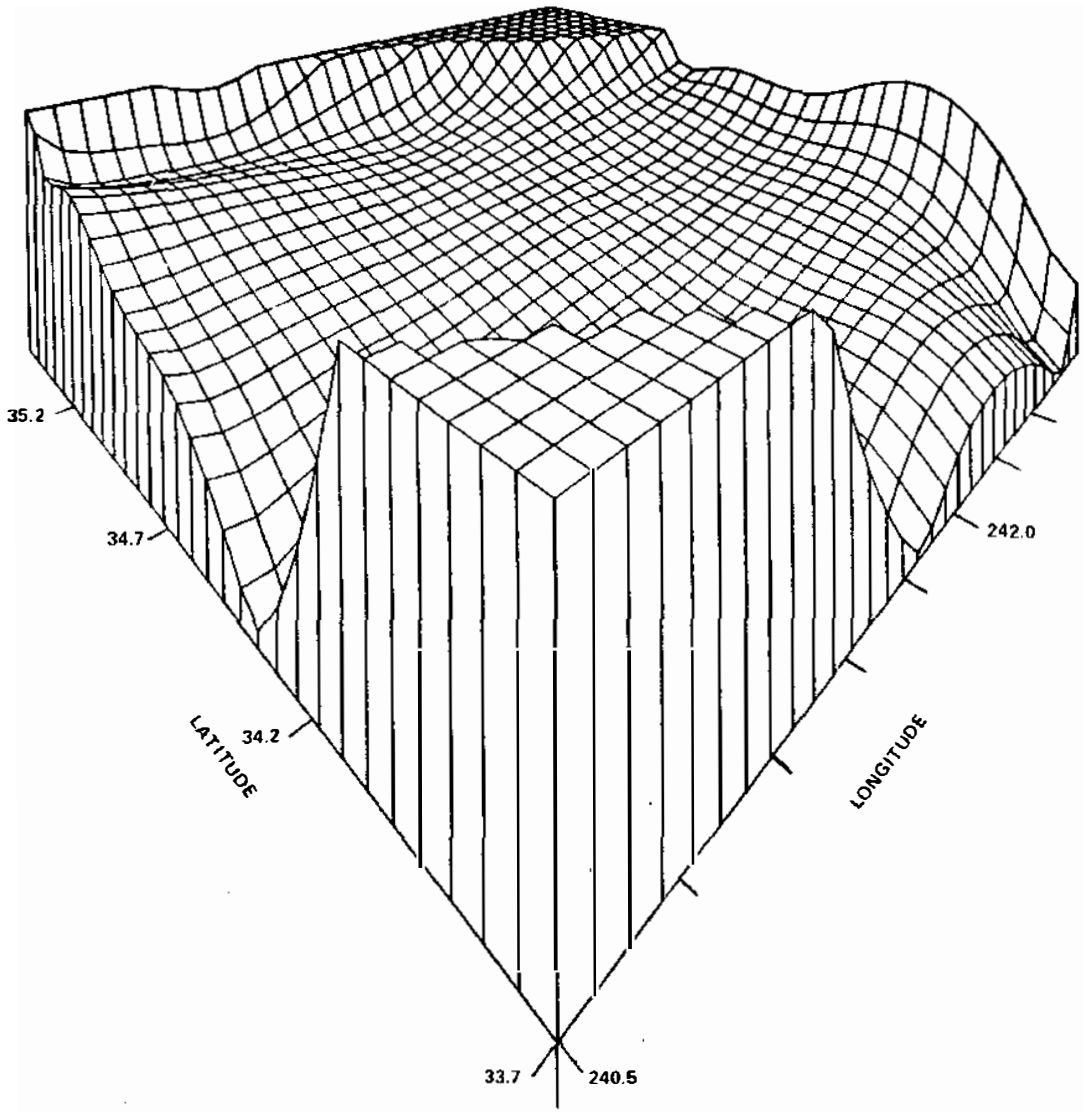

Figure 11.--Velocity error surface for Palmdale vicinity, 1959 to 1976.

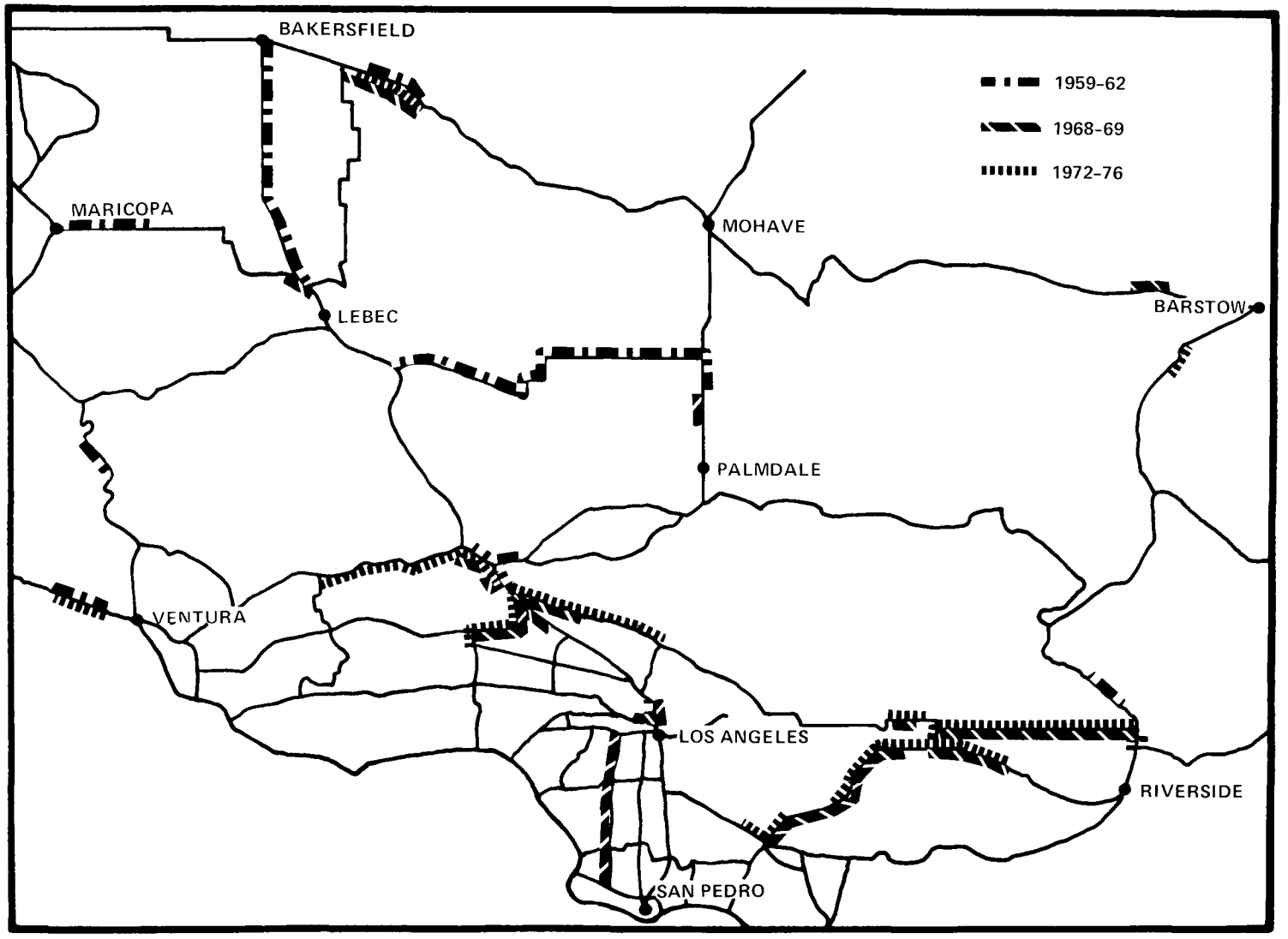

Figure 12.--Observations having excessive residuals.

were not outside the area affected by the 1952 Arvin-Tehachapi earthquake (adjustment I) and outside the area affected by the 1971 San Fernando earthquake (adjustment II). This latter suspicion is justified in figure 12, which shows the locations of observations taking large corrections in adjustment II.

Many of the plotted observations cluster near San Fernando. The plotted observations have residuals six times as large as their a priori standard deviations. It must also be acknowleged that a significant percentage of the aseismic vertical movement taking place in Southern California does not occur at constant rates. In fact, knowing where episodic aseismic movement is taking place may be of major importance to the seismologist. With this in mind, figure 12, or any similar illustration, should be studied carefully.

Figures 8 and 9 agree reasonably well with results first presented by Castle et al. (1976). The velocities given here indicate only 16.3 cm of uplift during the last 16 years, rather than the 25 cm first presented. However, when the NGS investigation was first performed, it included only the tidal record at San Pedro and none of the others. In that first analysis, higher uplift velocities were obtained, the maximum being 13.1 mm/yr at Lebec. Thus in some respects, the two analyses agreed more favorably prior to the introduction of additional tidal data. The zone of uplift determined here is somewhat to the north of the original maximum estimated to be at Palmdale, and no eastern terminus of the uplift is evidenced within the study area.

REFERENCES

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Holdahl, S. R., 1975: Models and strategies for computing vertical crustal movements in the United States. Presented to XVI General Assembly of the International Association of Geodesy, International Union of Geodesy and Geophysics, Symposium on Recent Crustal Movements, Grenoble, France, August 25 - September 6, 10 pp. Collected Reprints 1975 National Ocean Survey, National Oceanic and Atmospheric Administration, U. S. Department of Commerce, Rockville, Md., 173-187.